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Making the case for an alternate LBNF neutrino beam line.*

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Abstract

This note describes an alternate design (nuPIL) for the LBNF neutrino beam line. In order to make an informed decision whether or not to pursue this approach, the physics case first has to be made. In this note, we review the basic science requirements, give a brief description of the nuPIL concept and will show initial comparisons for CP sensitivity. We then will enumerate the minimum full set of physics analyses required to evaluate the overall performance of the LBNF/DUNE physics program for the case of the optimized LBNF conventional neutrino beam versus the neutrino beam available from a nuPIL configuration. The comparisons assume the same proton power on target and the same near and far detectors.

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I. INTRODUCTION

In order to make a decision regarding whether or not to proceed with a detailed cost-benefit analysis of a neutrinos from a pion beam line (nuPIL) neutrino beam for LBNF, vs. the current configuration for the beam, a comparison of the physics performance of the DUNE suite of detectors using the current best estimate for the neutrino fluxes available in the two configurations must be completed in time for the DUNE collaboration meeting in May. This document will outline the first set of comparisons based on the LBNF 80 GeV optimized beam line design and nuPIL lattice 11 design with only the bend (no beam line elements in the straight/decay pipe). A full set of comparisons will then need to be made in order to make a comprehensive presentation to the DUNE collaboration. It is hoped that these analyses plus a preliminary cost-differential analysis will allow the collaboration to make an informed decision regarding a recommendation to the LBNF project office to proceed with the detailed cost-benefit analysis.

II. BASIC REQUIREMENTS

Any change to the LBNF neutrino beam requirements is undesirable. Therefore the nuPIL design must meet the LBNF global science requirements for the beam line:

1. The neutrino beam spectrum shall cover the energy region of the first two oscillation maxima affected by muon-neutrino conversion from the atmospheric parameters. For a baseline of 1300 km, with the current knowledge of parameters, the first two nodes are expected to be approximately 2.4 and 0.8 GeV. The matter effects dominate over the CP effects above 3 GeV and the CP effect dominates below 1.5 GeV. Adequate number of electron neutrino events with good energy resolution will allow DUNE to exploit this spectral information to determine mass hierarchy, CP phase, and a precise value of θ_{13} unambiguously. The beam spectrum will also allow muon disappearance measurement with two nodes.

2. The beam shall be sign-selected to provide separate neutrino and anti-neutrino beams with high purity to enable measurement of CP violation mass hierarchy, and precision oscillation measurement.

3. The electron neutrino content in the beam shall be kept small so that the systematic errors on the additional background has a small impact on the CP phase measurement (compared to the statistical error).

4. The neutrino beam spectrum shall extend beyond the first maximum to higher energies, while maintaining a high signal to background ratio to obtain the maximum number of charged current signal events. This will allow precision probes of the PMNS parameters that govern neutrino oscillations.

5. The beam shall be aimed at the far detector with an angular accuracy that allows the determination of the far detector spectrum using the near detector measurements. The angular accuracy shall not be the dominant factor in the determination of oscillation parameters.

6. The beam shall be capable of operating with a single-turn, fast-extracted primary proton beam from the Main Injector with greater than 2 MW of power. The fast extraction enables short spills which are essential for good cosmic ray background rejection for detectors.

7. The beam line shall be able to accept a range of Main Injector proton energies that is well matched to the oscillation physics requirements. Proton beam energies of around 60 GeV are optimal for the simultaneous measurements of CP violation and MH, while higher energy beams (the maximum possible from the Main Injector is 150 GeV) can probe physics beyond the 3-flavor mixing, and probe tau-appearance with higher statistics.

In addition, the basic physics requirements are:

1. For CP 3 σ sensitivity over 75% of the δ_{CP} range with an 850 kt*MW*yr exposure.

2. Resolution on δ_{CP} of better than 20 degrees.

3. Precision measurement of all oscillation parameters including θ_{13}.

III. NEUTRINO FLUXES FOR INITIAL STUDY

In order to provide a first physics comparison for the DUNE collaboration meeting in May, nuPIL lattice 11 was chosen as the baseline for the bend and no beam line elements in the straight (decay pipe) were assumed. A 4 m diameter by 204 m long decay pipe is assumed, as is the case in the baseline LBNF design. Work continues on matching the bend to the straight beam line elements (the preferred implementation, we believe) and a complete (horn to decay straight end) nuPIL bean line configuration should be available for study shortly after the DUNE collaboration meeting.

A. nuPIL lattice 11

The basic concept for the nuPIL beam line design is an outgrowth of the nuSTORM pion beam line [1, 2]. Concepts for nuPIL have gone through 13 lattice designs to date. We have chosen lattice 11 for this study. Lattice 11 is an achromatic beam line composed of a dispersion creator and two bending matching cells, made of scaling FFAG magnets as shown in Figure 1. There are 10 elements in the bend with the trajectory dropping 2 m from the downstream end of the horn. Table I gives the parameters of the magnets in the bend and Table II gives the lattice description.

Table I. Parameters of the magnets.

Magnet type	Number of magnets	Excursion [m]	Length [m]	Gap size [m]	B_{max} [T]	B_{min} [T]	L_{coil} [m]
F1	4	0.82	2.6	0.66	1.48	0.11	7.5
D1	2	0.72	4.0	0.66	1.29	0.13	10
F5	1	0.92	4.6	0.66	0.50	0.12	11.5
D3	1	0.84	3.3	0.66	0.52	0.14	9
D4	1	0.87	1.6	0.66	1.64	0.41	5.5
F5	1	0.80	2.2	0.66	1.35	0.38	6.5

Figure 2 shows the evolution of the transmitted pion momentum distribution from the downstream face of the horn to the end of the bend and Figure 3 shows representative particle trajectories through the bend.

Table II. Lattice parameters of the nuPIL FFAG bend.

Dispersion creator	FDF triplet $\times 2$
radius (5 GeV/c)	386.3
k-value	1240
periodic dispersion [m]	0.31
final dispersion [m]	0.62
opening angle [deg]	1.7 $\times 2$
final excursion (3-10 GeV/c) [m]	0.75
length [m]	23
phase advance (H/V) [deg]	(65, 187)
max magnetic field [T]	1.5
Bending cell 1	FD doublet
radius (5 GeV/c)	541.2
k-value	867.8
opening angle [deg]	1.2
periodic dispersion [m]	0.62
length [m]	11
Final beta [m] (5 GeV/c) (H/V)	(8.4, 48.1)
max magnetic field [T]	0.6
Bending cell 2	DF doublet
radius (5 GeV/c)	255.0
k-value	408.4
opening angle [deg]	1.2
periodic dispersion [m]	0.62
length [m]	5
Final beta [m] (5 GeV/c) (H/V)	(26.6, 24.1)
max magnetic field [T]	1.5

B. Neutrino flux

The nuPIL fluxes have been calculated using a nuSTORM horn with a 38 cm long (2.5 interaction length) Inconel target. Optimization of the target/horn module for the nuPIL lattice has not yet been done, but will start soon. Production off the target and through the horn (nuSTORM baseline which was "NuMI-like") was simulated with MARS15 using realistic horn material parameters. This parent particle distribution (pions, Kaons and protons) at the downstream face of the horn was tracked through the bend using the Lagrange code, which has been cross-checked against Zgoubi [3] and bench-marked by experiment [4]. All

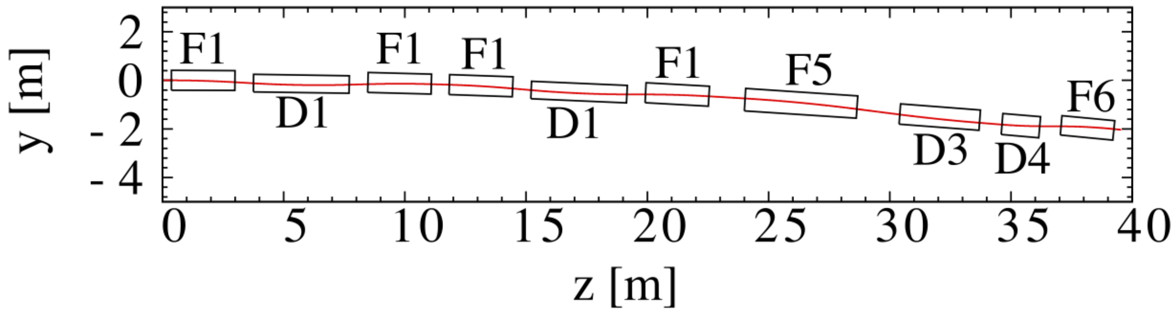

Figure 1. Layout of the nuPIL bend (lattice 11) with the magnet types labeled. The black lines show the effective field boundaries of the magnets.

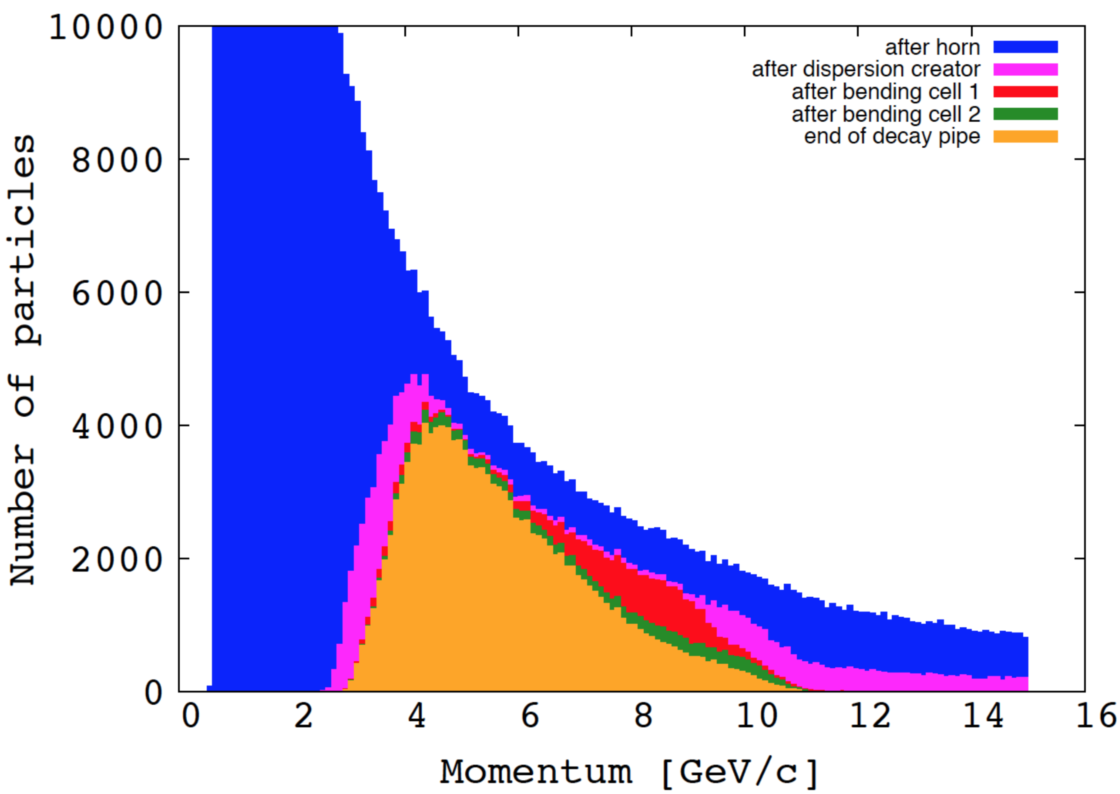

Figure 2. Momentum distribution of transmitted pions along the FFAG bend.

pions, kaons and protons exiting the horn and within the aperture of the first beam line element are tracked. For the neutrino beam, π^- and K^- are also tracked and vice versa for the anti-neutrino beam.

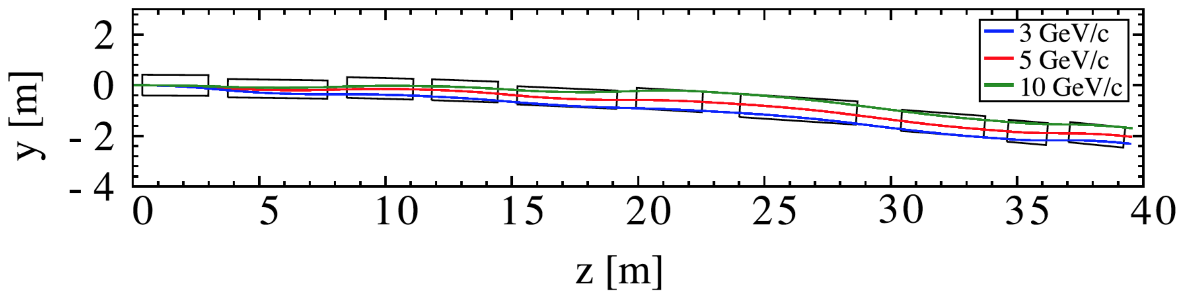

Figure 3. FFAG bend. Trajectories for 3, 5 and 10 GeV/c particles are shown.

1. Flux at the Far Detector

Figure 4 gives the neutrino beam ($\nu_\mu, \bar{\nu}_\mu$ and ν_e) for the LBNF 80 GeV optimized beam and for the nuPIL lattice 11 beam, based on particle distributions exiting the bend, as described in the preceding paragraph. The anti-neutrino beam is given in Figure 5.

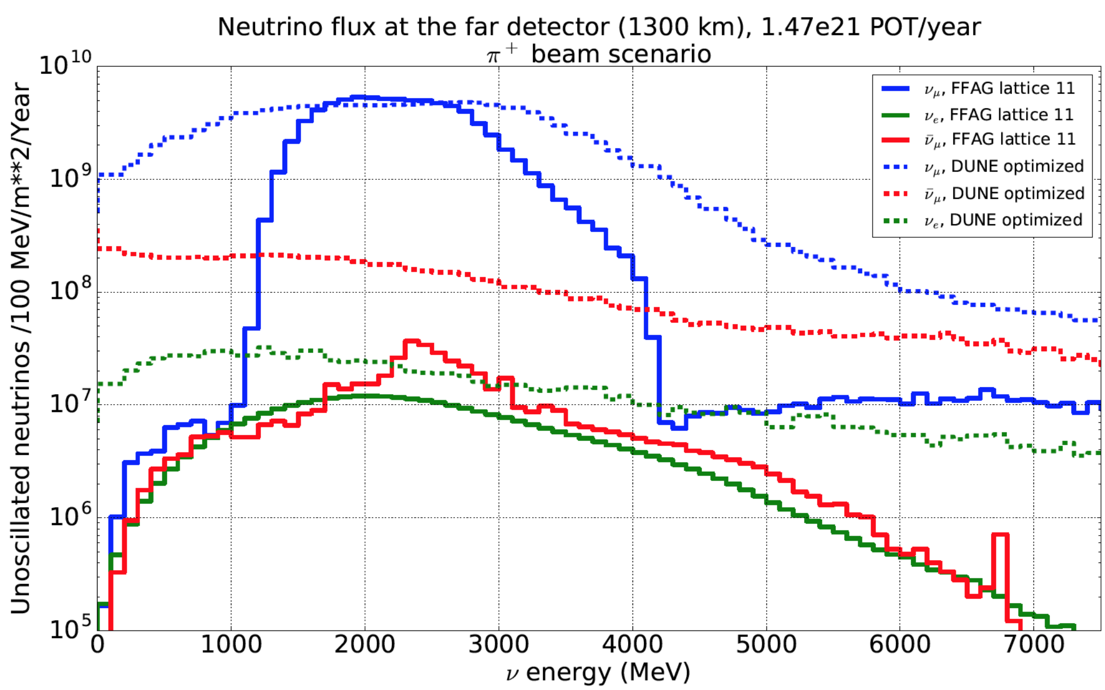

Figure 4. Neutrino fluxes for the optimized 80 GeV LBNF beam and the nuPIL beam (including all backgrounds.)

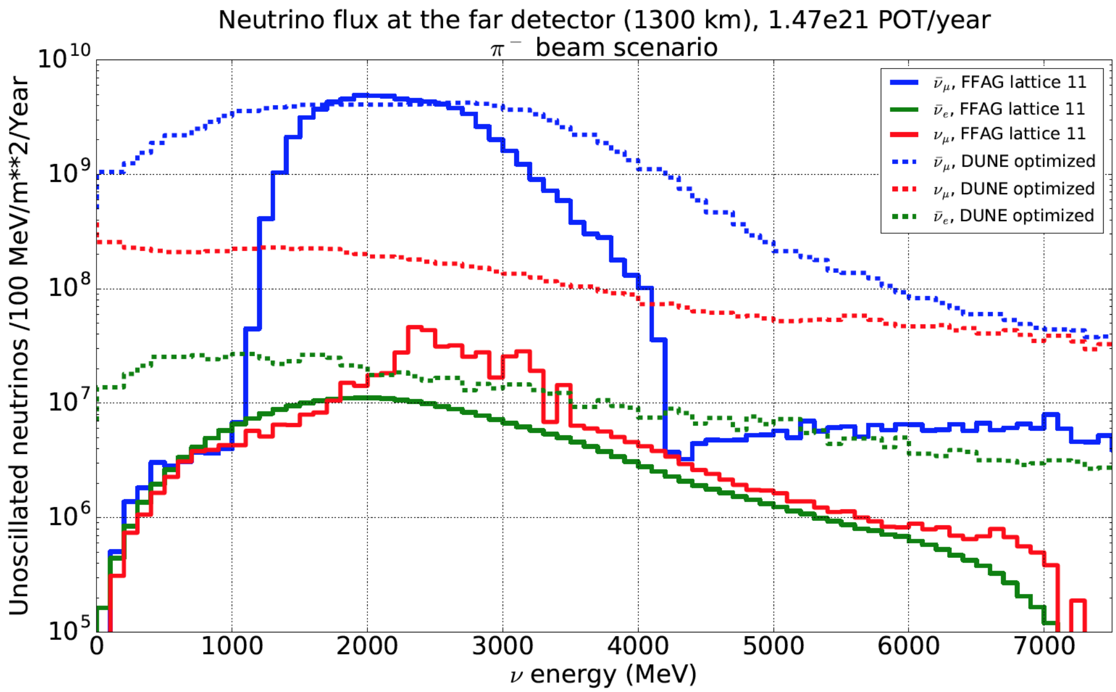

Figure 5. Anti-Neutrino fluxes for the optimized 80 GeV LBNF beam and the nuPIL beam (including all backgrounds.)

2. Flux at the Near Detector

In a nuPIL configuration for LBNF, the beam design allows for the near detector hall to be located much closer to the end of the decay straight due to the fact that there is no high-energy component (pions, muons or protons) in the beam. In the nuPIL configuration, the near detector hall can be located 50 m from the end of the straight. See Figure 6. This configuration yields a potential large cost savings in civil construction. The neutrino and anti-neutrino fluxes given below have assumed a near detector hall position that is 454 m from the end of the bend, however. This is similar to the near detector hall position in LBNF. The ND site neutrino and anti-neutrino fluxes are given in Figures 7 and 8 respectively. For comparison, the neutrino and anti-neutrino fluxes at a near hall site as indicated in Figure 6 are given in Figures 9 and 10, respectively.

C. Computing Sensitivities

In order to efficiently compare and benchmark NuPIL versus LBNF conventional, it was agreed to engage with the DUNE LBWG to compute sensitivities (to avoid the arguments

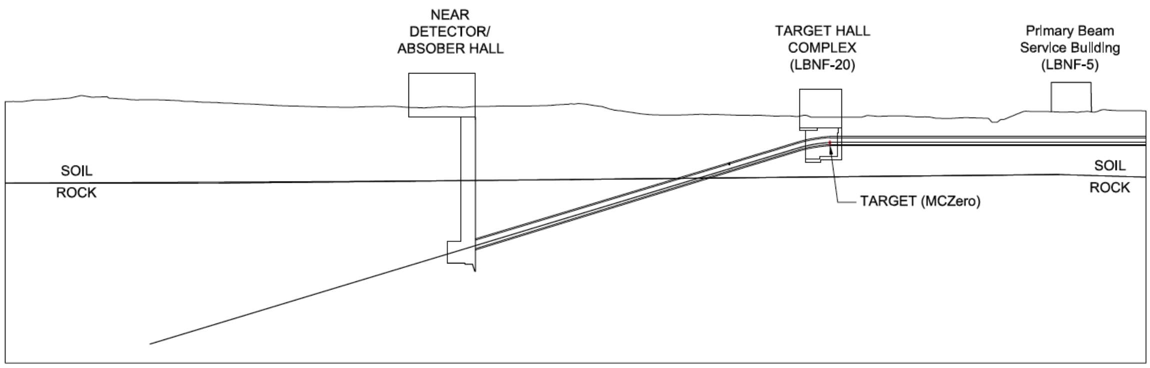

Figure 6. Near detector hall configuration for nuPIL.

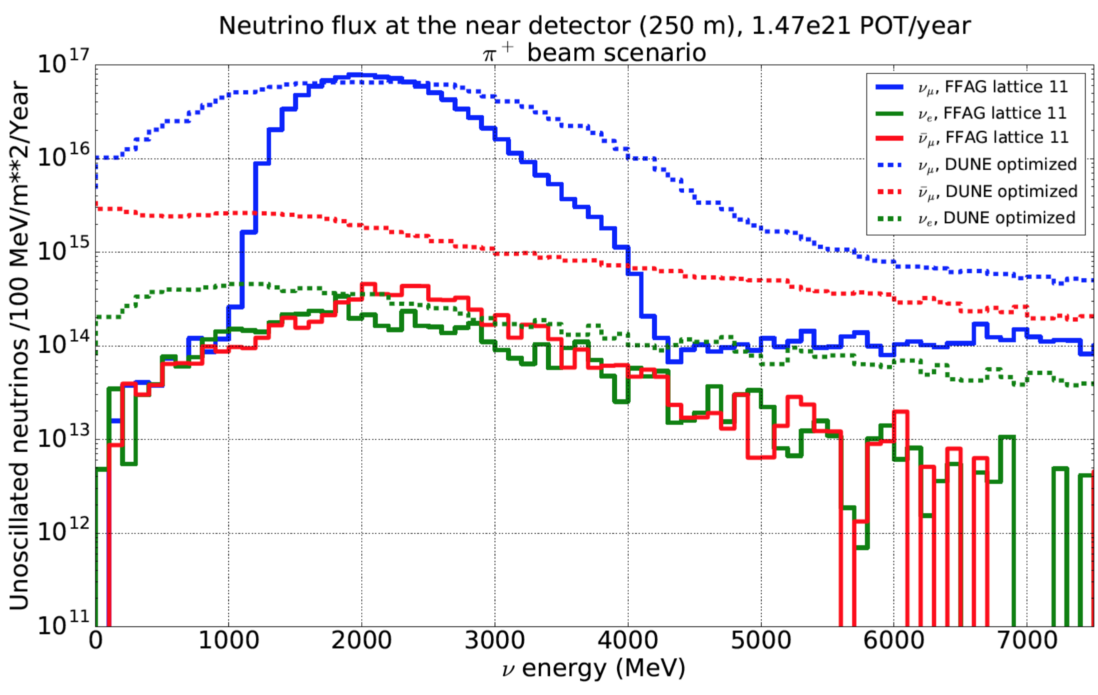

Figure 7. Neutrino flux at the nuPIL near hall site at a position 454 m from the end of the bend.

if his sensitivity calculation is right or wrong). The LBWG, once provided with the fluxes (see above), will provide the standard benchmark plots i.e. CPV, MH, θ_{23} vs. δ_{CP}, θ_{13} vs. δ, etc. to be presented at the DUNE Collaboration meeting.

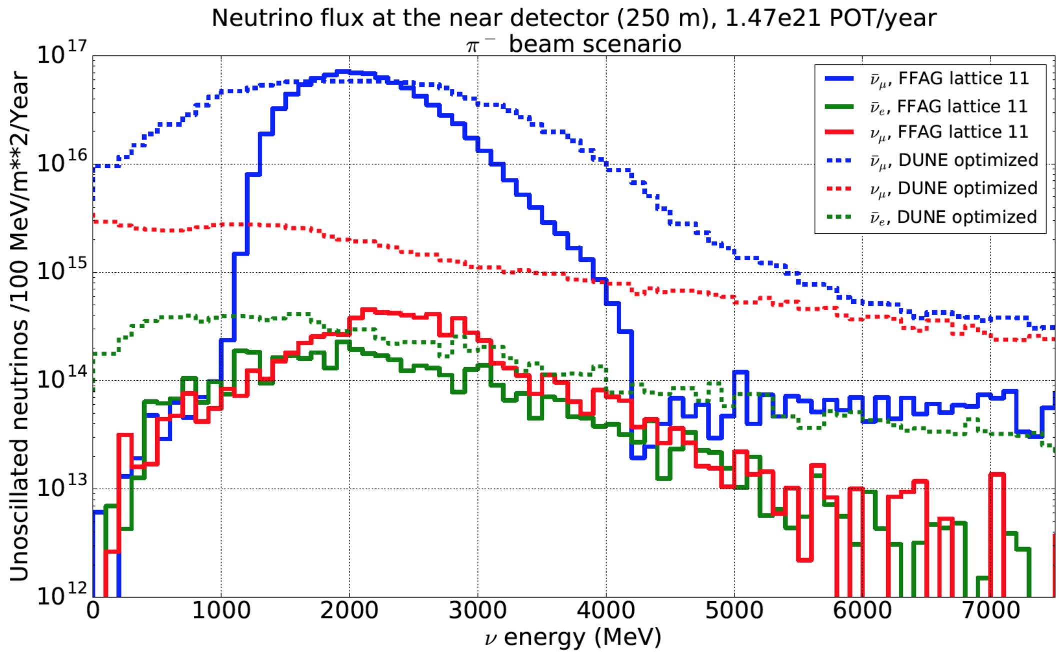

Figure 8. Anti-neutrino flux at the nuPIL near hall site at a position 454 m from the end of the bend.

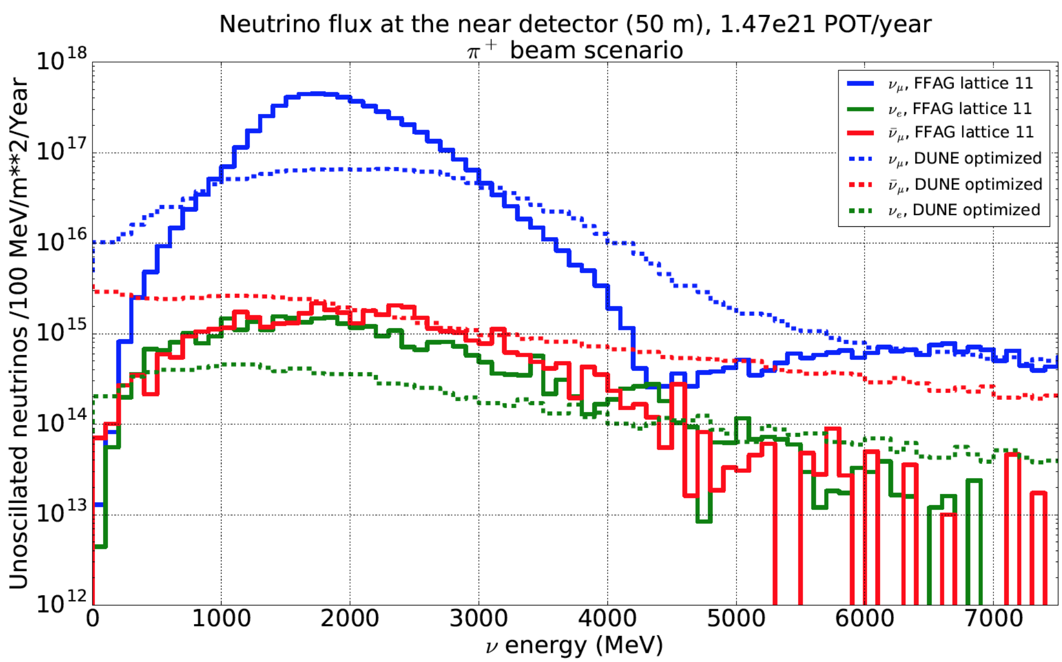

Figure 9. Neutrino flux at the nuPIL near hall site at a position 254 m from the end of the bend.

IV. ANALYSIS SUITE OVERVIEW

In order to fully understand the physics potential of a nuPIL configuration, physics comparisons will include the basic long-baseline measurements as well as well as rate comparisons at

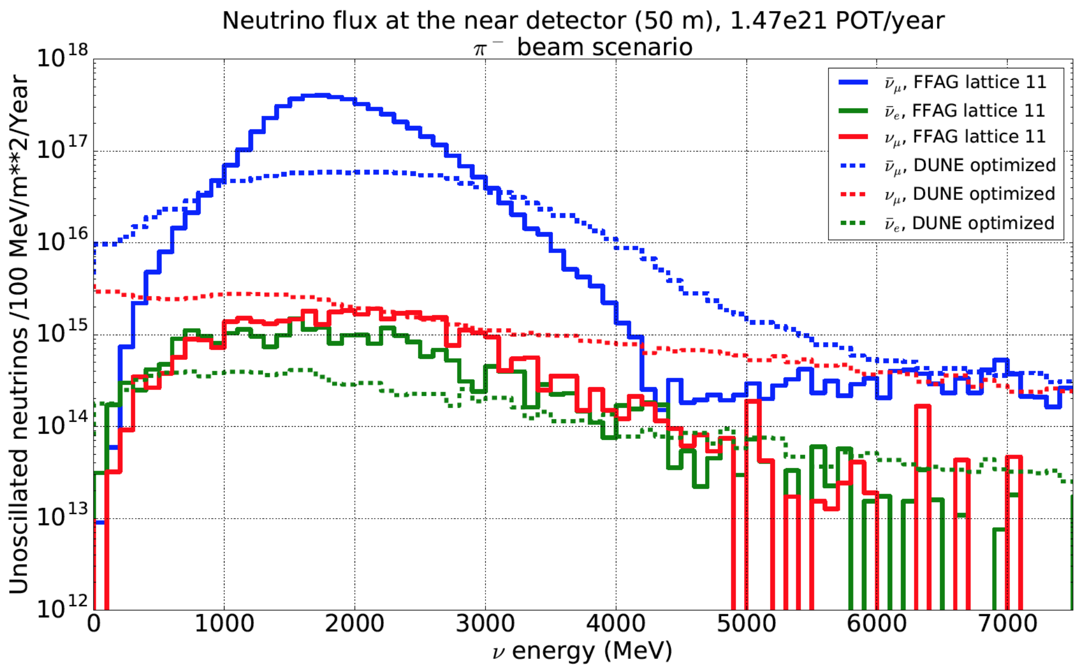

Figure 10. Anti-neutrino flux at the nuPIL near hall site at a position 254 m from the end of the bend.

the near-detector site. Some preliminary evaluations of the differences that the two beams may present with respect to physics beyond the νSM will also be given.

A. Far site

Long-baseline physics comparisons will include:

1. Mass hierarchy

2. CP coverage

3. CP sensitivity as a function of exposure for 75% CP coverage

4. δ_{CP} resolution as a function of exposure

5. θ_{23} resolution

B. Near site

C. Beam systematics

Some of the comparisons in Section IV A will be done for beam normalization uncertainties in the two configurations where these uncertainties are twice as large as anticipated. In addition, a comparison will be made in which the near-far flux extrapolation uncertainty is twice what has been calculated.

D. Hypotheticals

Some hypotheticals regarding detector performance will also be study. A comparison of the CP reach of the conventional LBNF flux to that of nuPIL will be done for the following hypotheticals:

1. NC background is 4%

2. The missing energy uncertainty is 50%

E. Physics beyond the νSM

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1. NSI

2. Steriles

3. DM

4. τ appearance

V. CONCLUSIONS

[1] D. Adey, R. Bayes, A. Bross, and P. Snopok, Ann. Rev. Nucl. Part. Sci. **65**, 145 (2015).

[2] A. D. Bross, A. Liu, J.-B. Lagrange, and J. Pasternak, PoS **EPS-HEP2015**, 065 (2015).

[3] F. Meot, Nucl. Instrum. Meth. **A767**, 112 (2014).

[4] J. B. Lagrange, T. Planche, E. Yamakawa, T. Uesugi, Y. Ishi, Y. Kuriyama, B. Qin, K. Okabe, and Y. Mori, Nucl. Instrum. Meth. **A691**, 55 (2012).